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Diverging forest land use dynamics induced by armed conflict across the tropics

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ABSTRACT

Armed conflicts trigger region-specific mechanisms that affect land use change. Deforestation is presented as one of the most common negative environmental impacts resulting from armed conflicts, with relevant consequences in terms of greenhouse gas emissions and loss of ecosystem services. However, the impact of armed conflict on forests is complex and may simultaneously lead to positive and negative environmental outcomes, i.e. forest regrowth and deforestation, in different regions even within a country. We investigate the impact that armed conflict exerted over forest dynamics at different spatial scales in Colombia and for the global tropics during the period 1992–2015. Through the analysis of its internally displaced population (departures) our results suggest that, albeit finding forest regrowth in some municipalities, the Colombian conflict predominantly exerted a negative impact on its forests. A further examination of georeferenced fighting locations in Colombia and across the globe shows that conflict areas were 8 and 4 times more likely to undergo deforestation, respectively, in the following years in relation to average deforestation rates. This study represents a municipality level, long-term spatial analysis of the diverging effects the Colombian conflict exerted over its forest dynamics over two distinct periods of increasing and decreasing conflict intensity. Moreover, it presents the first quantified estimate of conflict's negative impact on forest ecosystems across the globe. The relationship between armed conflict and land use change is of global relevance given the recent increase of armed conflicts across the world and the importance of a possible exacerbation of armed conflicts and migration as climate change impacts increase.

1. Introduction

A growing body of literature has attempted to improve our understanding of the existing bi-directional relationships between armed conflicts (including warfare) and the environment (e.g. land use and climate). There is evidence relating past changes in temperature and precipitation to the onset of armed conflict through region-specific mechanisms (Scheffran et al., 2012; Hsiang et al., 2013; Gleick, 2014; Schleussner et al., 2016; Werrell and Femia, 2017; Sterzel et al., 2014), suggesting that if future populations respond similarly to past populations, then anthropogenic climate change has the potential to substantially increase conflict around the world, relative to a world without climate change.

On the other hand, armed conflicts constitute the most drastic shocks that can impact societies and, in turn, affect land use change (LUC). Although several types of LUC are possible (Baumann and Kuemmerle, 2016), those affecting forest land use (LU) are of particular interest, given their crucial role in carbon storage and provisioning of ecosystem services (Foley, 2005; Baccini et al., 2012). Deforestation represents the most negative environmental impact arising from armed conflict (Baumann and Kuemmerle, 2016; Suarez et al., 2017) and forests are reported to have suffered during times of violence in the Democratic Republic of Congo (Butsic et al., 2015; Nackoney et al., 2014), Rwanda (Ordway, 2015), Vietnam (Van et al., 2015) and in regions of Central Africa (Basnet and Vodacek, 2015). However, the impact of conflict on forests is not unidirectional, and reported beneficial impacts also exist for Sierra Leone (Burgess et al., 2015; Wilson and Wilson, 2012), South Sudan (Gorsevski et al., 2012), El Salvador (Hecht et al., 2006), Cambodia (Le Billon, 2000) and Nicaragua (Berhe, 2007).

Albeit forest ecosystems can suffer directly in some extreme cases [e.g. defoliation with Agent Orange during the Vietnam War (Van et al., 2015)], armed conflicts' impact on forests are more likely to occur through an increase or decrease of existing regional drivers of LUC by

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different mechanisms. For instance, the displacement of local population (Hagenlocher et al., 2012), the use of landmines (Berhe, 2007), the need of natural resources to finance warfare efforts (Global Witness, 2013), unstable political institutions or insecure land tenure (Dávalos, 2001) resulting from armed conflict exert an important impact in deforestation drivers such as logging, mining or agriculture production.

Casualties and forceful displacement of population [e.g. internally-displaced persons (IDPs)] constitute two of the most tragic consequences arising from armed conflicts. Colombia ranks amongst the top countries in the world in regards to the latter, with over 7 million persons displaced from their home towns, representing a key factor of Colombian demographics (Negret et al., 2017). Surprisingly though, albeit conflict-induced migration exerted an important impact in terms of LUC dynamics in Colombia, the relationship between armed conflict and forest ecosystems has been analyzed mostly for small regions or has focused on a particular conflict-related impact on forests (Álvarez, 2001; Álvarez, 2003; Dávalos, 2001; Dávalos et al., 2011; Rincón-Ruiz and Kallis, 2013), with few exceptions that focus on recent periods characterized by a gradual decrease of conflict intensity (Sánchez-Cuervo and Aide, 2013; Castro-Nunez et al., 2017).

A recent review of armed conflicts' impacts on land systems (Baumann and Kuemmerle, 2016) highlights the need for further long-term studies in this field that empirically link conflict and LUC. Despite the proliferation of high-resolution land cover, deforestation and armed conflict datasets, long-term systematic analyses are still missing. Additionally, despite the increase in georeferenced conflict data global assessments are lacking and there has been no attempt to explore the direct LUC impacts of fighting locations.

To address these research gaps, we conduct a case study for Colombia to identify, firstly, the diverse armed conflict-forest dynamics existing for the 1992–2015 period and the deforestation/forest regrowth pathways found at a municipality and department scales. Secondly, this study explores georeferenced fighting locations – both for Colombia and the global tropics – to determine whether armed conflict exerted a direct impact on LUC.

To answer the first question we analyze LU datasets covering the 24-year period with Colombian municipality-level data on departure IDPs and conflict casualties. This represents by far the longest time frame analyzed to date and allows to include two distinct periods of increasing and decreasing conflict intensity. Additionally, it provides municipality-level results for Colombia. The second question seeks to understand for the first time whether conflict locations are more or less likely to undergo LUC in relation to average LUC rates.

2. Materials and methods

In the following sections we present the land cover data employed in the analyses, the different variables selected to represent different degrees of conflict intensity - internally displaced persons (IDPs) and conflict-related casualties, and the dataset on conflict event locations. The different nature of the variables used lead to two different methodological approaches, which are described below and are summarized in Table 1.

2.1. Land cover change

To describe forest LUC occurring in Colombia we use a recently released 300 m resolution land cover dataset produced by the European Space Agency – the Climate Change Initiative Land Cover dataset (CCI-LC) (ESA, 2017). It provides yearly information on 21 different land cover classes for the 24-year period of 1992–2015. We aggregate the different forest classes into one forest category (Fig. 1a) that is consistent with the IPCC's forest definition (Table A.1).

In order to capture the overall positive or negative effects across municipalities, i.e. forest recovery or loss, we consider the yearly evolution of total forest LU for each municipality during the 1992–2015 period, which includes deforestation and forest regrowth dynamics. Deforestation is used in this work to describe a loss of forest LU (e.g. forest to cropland) and forest regrowth analogously describes changes from non-forest to forest LU.

2.2. Internally displaced persons and armed conflict casualties

We use two different conflict intensity variables and determine their relationship to forest LUC. Firstly, we use municipality-level data on Colombian IDP departures, defined as 'persons or groups of persons who have been forced or obliged to flee or to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights or natural or human-made disasters, and who have not crossed an internationally recognized border' (RUV, 2016). From this dataset, produced by the Colombian government, we retrieve yearly information on the number of citizens that were forced to leave their hometowns for the 1992–2015 period at a municipality level (Fig. 1b). Secondly, we use conflict-related casualties from the Uppsala Conflict Data Program Georeferenced Event Dataset (UCDP GED) (Sundberg and Melander, 2013), which provides world-wide spatially and temporally disaggregated data on conflict events, defined as instances of organized violence that present at least one fatality. This data only allows sufficient data points for a department-level analysis. Higher numbers of IDP departures and casualties are assumed to represent higher degrees of conflict intensity, and vice versa.

Based on the insight that conflict can be understood as a valve that modulates (i.e. increases or decreases) the intensity of existing regional underlying drivers (Baumann and Kuemmerle, 2016) and assuming a linear relationship, we perform Pearson correlation tests to determine the direction and strength of the relationship found between forest LU and the two conflict variables presented for two scales (across 1120 municipalities and 32 departments). We chose $R^2 > 0.5$ as a benchmark to define a strong relationship. From the analysis of both conflict-related variables (IDPs and conflict casualties) we identify for the 1992–2015 period the regions in which Colombian forests could have benefited or suffered as a result of different degrees of conflict intensity.

2.3. Location of conflict events

Next, we seek to understand more on the LUC occurring at

Table 1
Summary of datasets used for the study.

Dataset	Source	Description	Resolution	Period
Climate Change Initiative Land Cover dataset (CCI-LC)	ESA (2017)	Global land use dataset, 21 land cover classes	300 m, year	1992-2015
Internally displaced persons (IDPs, departures)	RUV (2016)	Forcefully displaced persons in Colombia	Municipality, year	1992–2015
Conflict casualties	Sundberg (2016)	Number of fatalities resulting from armed conflict in Colombia	Aggregated to department level, year	1992–2015
Conflict Event Location	Sundberg (2016)	Fighting locations in Colombia (N = 1489)	Georeferenced, year	1992–2015
Conflict Event Location	Sundberg (2016)	Fighting locations in the global tropics (N = 20, 967)	Georeferenced, year	1992–2015

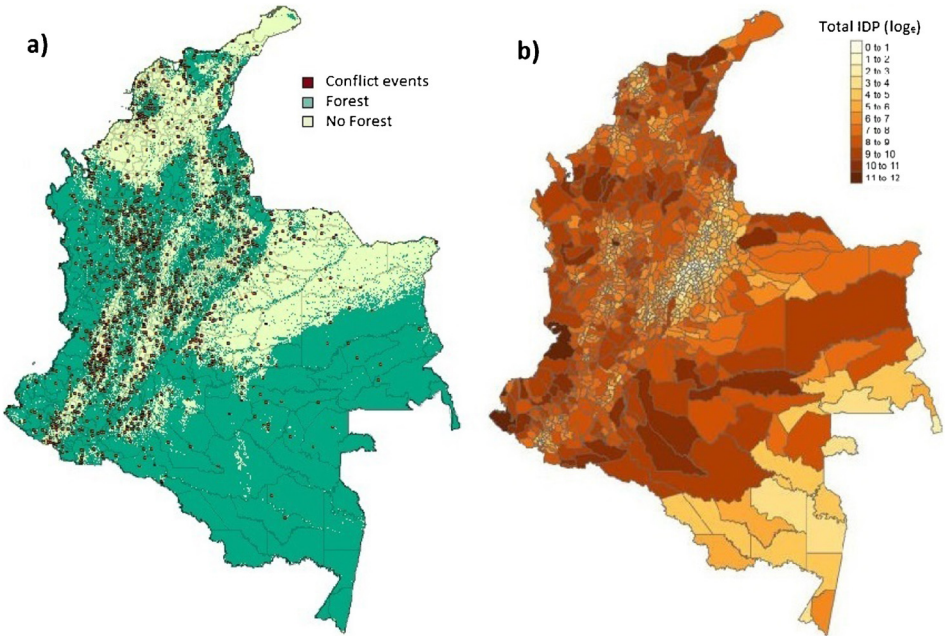

Fig. 1. Land use and armed conflict data. (a) presents an example of a forest/non-forest land use map for the year 1992 derived from the Climate Change Initiative Land Cover dataset. Superimposed are the aggregated 1992–2015 conflict event locations (i.e. the georeferenced locations where the fighting took place). (b) illustrates the distribution of internally displaced persons (departures) aggregated for the 1992–2015 period at the Colombian municipality level (log_e scale).

georeferenced armed conflict locations. This is performed as a complementary analysis to the previous exercise for validating its results at a country-scale through a spatially-explicit approach. For this, we obtain a total of 4,234 conflict events from the UCDP GED dataset for the time period of 1992–2015 in Colombia (Sundberg and Melander, 2013). From these events we select the 1,489 conflict events that present an exact georeferenced location (Fig. 1a). Then, for each year, we superimpose all individual conflict events with the LU information of the CCI-LC dataset and evaluate the changes that occur in forested conflict locations in the following year, i.e. we calculate the percentage of forest conflict pixels that are deforested during the 1992–2015 period.

In order to interpret the relevance of the LUC found at the conflict locations, we compare them to the maximum and mean deforestation rates produced by simulations that use random resampling. In a first step, the 1,489 conflict events are disaggregated per year; then, for each year the same number of conflict events are randomly resampled at a country scale and the total percentage of deforested pixels is again calculated for the whole period. The statistical significance of the LUC taking place at conflict locations is determined by comparing it to the distribution of deforestation rates produced by 1,000 simulations.

This evaluation is similarly performed to analyze the forest regrowth dynamics occurring at conflict locations, i.e. we compare the percentage of forest regrowth of non-forested conflict locations and compare it to the percentages produced by 1,000 simulations that use random resampling. However, there are some differences for the analysis of forest regrowth: firstly, we obtain the percentages of non-forest conflict pixels that change to forest class after 5 years and by the end of the 1992–2015 period (instead of the following year). We consider two longer periods to account for the slower nature of non-forest to forest LUC. Secondly, the LU of 'settlement' (i.e. villages and urban settings) is not considered when calculating the percentage of forest regrowth. This LU category is unlikely to present forest regrowth and could distort the meaning of the results when compared to the simulations, since the percentage of conflicts taking place in urban settings is larger than the LU share of 'settlement' in Colombia.

2.4. Deforestation and armed conflict across the tropics

To obtain a global estimate of armed conflict's impact on LUC, we apply the methodology described in the previous section at a global scale for the entire tropics, which includes data from 66 countries (Fig. 2, Tables A.3 and A.4). We calculate the forest loss rate of 20,967 georeferenced conflict events and compare it to the deforestation percentages produced by 100 simulations that use random resampling.

3. Results

3.1. Internally displaced persons, conflict casualties and forest land use change

We observe two distinct armed conflict-forest LUC pathways occurring in municipalities that present a strong relationship between forests and IDPs ($R^2 > 0.5$; $p < 0.01$): we find a 'forest regrowth pathway', in which municipalities showed a recovery of its forests in the midst of an increasing number of displaced population (Fig. 3a).

Existing literature attempts to explain this 'forest regrowth pathway' based on the combination of three mechanisms (Fig. 4). For instance, the violent and insecure context of the armed conflict accelerated land abandonment and promoted predominantly a rural to urban migration (Negret et al., 2017). This in turn encouraged forest regrowth in many agricultural areas, particularly the ones found in non-optimal environmental conditions for economic activities (Sánchez-Cuervo and Aide, 2013; Negret et al., 2017). Moreover, conflict actors are reported to have favored a forest conservation of sorts in the form of land access restrictions, enforced with land mines and civilian curfews in strategically important areas (Álvarez (2003) defined this type of coercion as 'gunpoint conservation'). Finally, as an indirect effect of the armed conflict, some forest areas benefited from being increasingly isolated from development occurring in other regions of the country (Dávalos, 2001).

In contrast, we also find a 'deforestation pathway' in municipalities where forest cover loss is observed despite an increasing number of forcefully displaced inhabitants (Fig. 3b). In these areas forest cover decreased as a result of one or several combined mechanisms (Fig. 4): firstly, the need to finance conflict efforts increased proximate deforestation drivers such as illicit crop production of coca (*Erythroxylum* sp.) or opium poppy (*Papaver somniferum*), mining and logging (Álvarez, 2003). Secondly, insecure land tenure and unstable political institutions increase the phenomenon of land grabbing by smallholder farmers and ensuing cattle pasture expansion (Dávalos et al., 2014). Removing forest cover to establish a herd of cattle strengthens land claims, even if clearing and ranching are not economically profitable. Finally, the

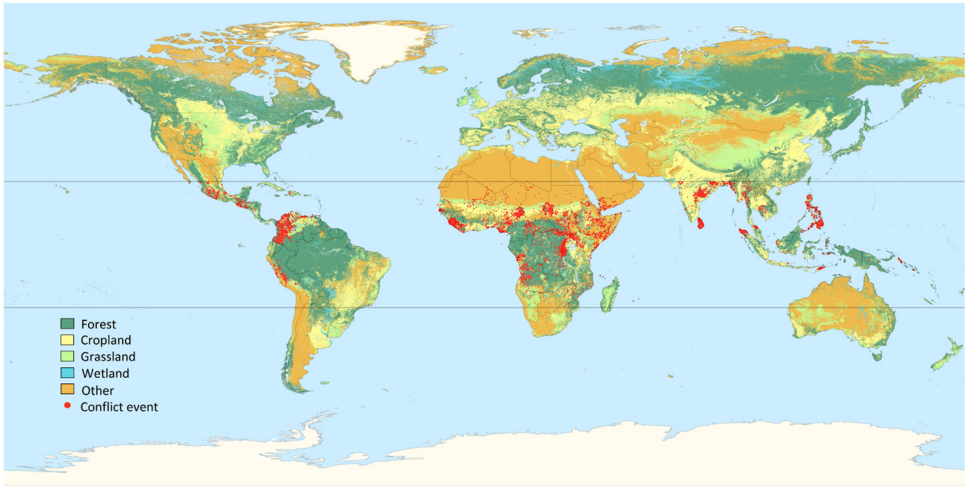

Fig. 2. Land use and armed conflict event data across the tropics. Global land use map for the year 1992 derived from the Climate Change Initiative Land Cover dataset. The IPCC LU classes are represented (forests in green). Superimposed are the aggregated 1992–2015 conflict event locations (red) occurring in the tropics, i.e. the georeferenced locations where the fighting took place. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

government's eradication of illicit crops through means of aerial fumigation with glyphosate was found to produce the opposite result it pursued, producing damage to the forest ecosystems under fumigation and displacing illicit crop production further into the forest (Álvarez, 2001; Pérez-Rincón, 2016).

The 'deforestation pathway' is observed in 139 municipalities, whereas the 'forest regrowth pathway' is present in 47 ($R^2 > 0.5$; $p < 0.01$) (Fig. 5a). Interestingly, despite finding positive impacts of conflict on forests at a municipality level, when aggregating the data at a higher department level (Fig. 5b), we find this positive effect to be in most cases too modest and is typically counterbalanced by municipalities presenting the opposite pattern: the deforestation impact of conflict is much stronger than forest regrowth dynamics.

As a result of these diverging effects across scales, only 2 departments out of Colombia's 32 analyzed exhibit an overall positive conflict-forest relationship pathway for the time period considered, while 14 present a negative effect (Fig. 5b). For example, the Nariño department, located in the southwestern region of Colombia (Fig. 5b – code 52), includes many municipalities displaying a 'forest regrowth pathway'. In spite of this, the effect of a few municipalities displaying the opposite negative pattern account for a higher relevance when the analysis is performed at a department scale. The westernmost municipality of the Nariño department is Tumaco. It presents a strong negative effect in our analysis, and corresponds in fact to the municipality with the highest percentage of illicit crop cultivation found in Colombia (UNODC, 2017).

Using auxiliary maps of the distribution of coca crops over the 2006–2015 period (UNODC, 2016) (Fig. A.1) we observe interesting overlaps between the "deforestation pathways" identified in this work and areas affected by coca crop cultivation for the departments of Nariño (code 52), Putumayo (86), Caquetá (18), Meta (50), Guaviare (95), Chocó (27), Santander (68) and Norte de Santander (54) (Fig. 5b). This comparison suggests that the "deforestation pathway" was likely most affected by the conflict financing mechanism in these departments. Illicit crop cultivation is the clearest example of land use employed to finance conflict efforts which deplete forest cover (Rincón-Ruiz and Kallis, 2013) – according to Echandia (1998), rebel group FARC (Revolutionary Armed Forces of Colombia) devoted about one third of its soldiers to direct or indirect coca-related activities. In these same areas, the government's efforts on illicit crops eradication likely acted in parallel, displacing coca production and local inhabitants further into the forest (Rincón-Ruiz and Kallis, 2013).

In contrast to these results, we found considerably weaker relationships between conflict and forest LU when adopting casualties (Sundberg and Melander, 2013) as a proxy of armed conflict intensity: only 2 departments out of 32 presented a strong relationship for the time period considered ($R^2 > 0.5$; $p < 0.01$) (Fig. A.2). We hypothesize two reasons for explaining this negative result: Firstly, a high number of registered casualties occurring in a single fighting event between two armed conflict actors might not translate into large impacts on local livelihoods nor changes in population dynamics in a given municipality, and in turn might not explain changes in LU. Secondly, armed conflict casualties are more likely to occur at the intersection of areas controlled by different conflict actors, but this does not

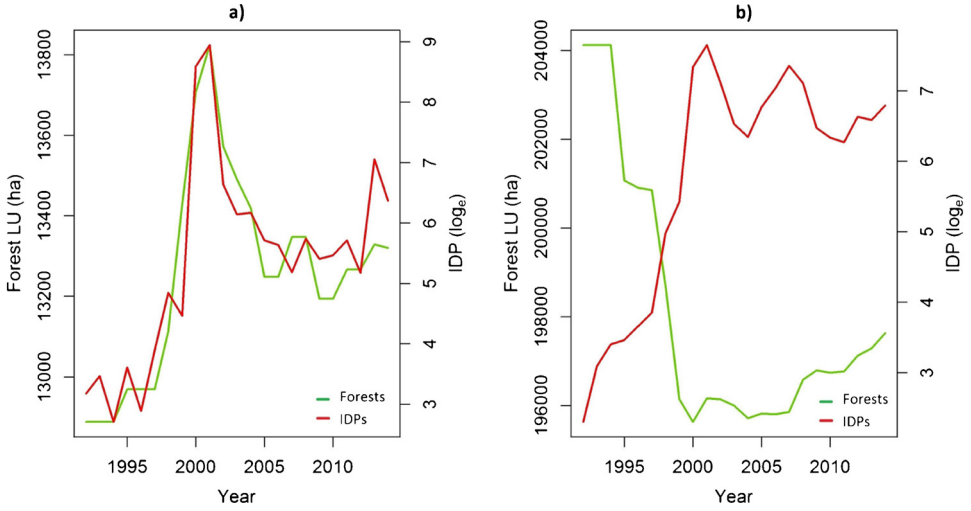

Fig. 3. Armed conflict intensity and forest land use change pathways. (a) presents an example of a positive relationship pattern ($R^2 = 0.84$; $p < 0.001$) ('forest regrowth pathway') found between forest land use (LU) and IDP departures (log_e) for the municipality of Buenos Aires (Cauca department): forest LU increases during higher degrees of armed conflict intensity, and vice versa – as the number of the forcefully displaced population reduces the pressure on forests increases. In (b) we observe an example of a negative relationship pattern ($R^2 = 0.88$; $p < 0.001$) ('deforestation pathway'), found for the municipality of Santa Rosa del Sur (Bolivar department): forest LU decreases despite an intensification of conflict.

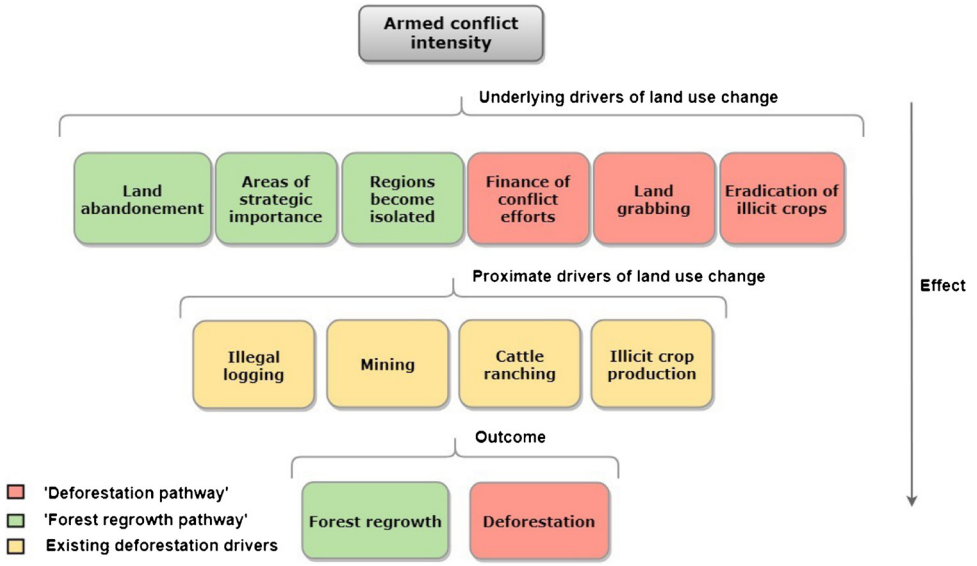

Fig. 4. Mechanisms through which armed conflict impacts forest ecosystems. Armed conflict impacts forests by altering the underlying drivers of land use change (e.g. the displacement of rural population, land access restrictions or the need to finance conflict efforts), which in turn increases or decreases the intensity of existing proximate drivers of land use change (e.g. illicit crop production, cattle ranching, etc.). Mechanisms that increase (red) and decrease (green) deforestation drivers lead to the 'deforestation pathway' and 'forest regrowth pathway', respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

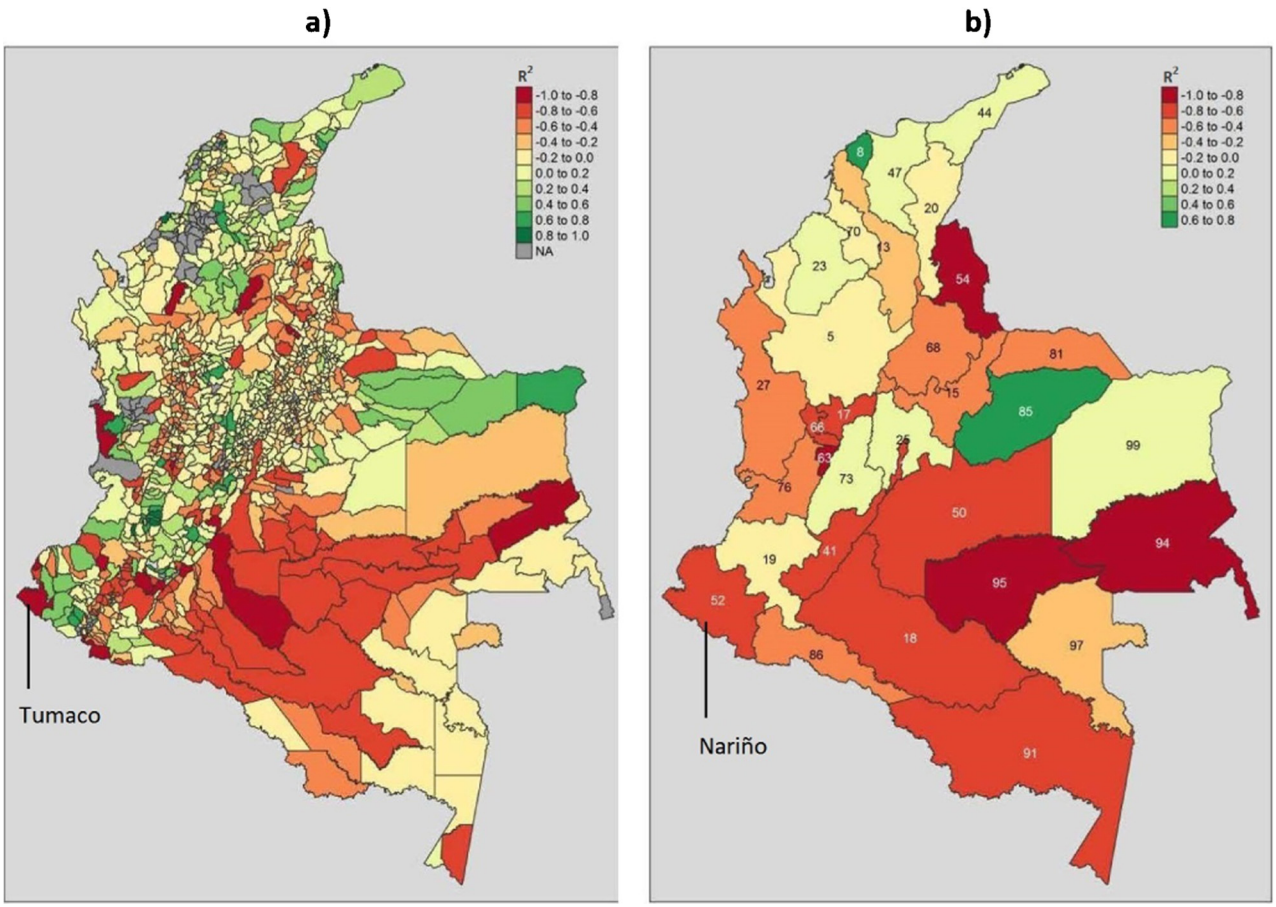

Fig. 5. Forest land use change and internally displaced persons – departures (log_e) correlation map for 1120 municipalities (a) and 32 departments (b) for the 1992–2015 period. Positive correlation (green) indicates forests recovering as higher degrees of conflict intensity unfold, i.e. the 'forest regrowth pathway' presented in Fig. 3a. Negative correlation (red) indicates forests suffering as higher degrees of conflict intensity unfold, i.e. the 'deforestation pathway' presented in Fig. 3b. Albeit finding municipalities with positive relationship patterns (a), when performing the analysis at a higher department level (b) it is clear that overall armed conflict exerted a negative effect over Colombian forests. Municipalities in grey (a) did not present either a variation of forest land use or of internally displaced persons in the time period considered. Negative values of R^2 are presented to indicate a negative relationship. The department codes are provided in Appendix (Table A.2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

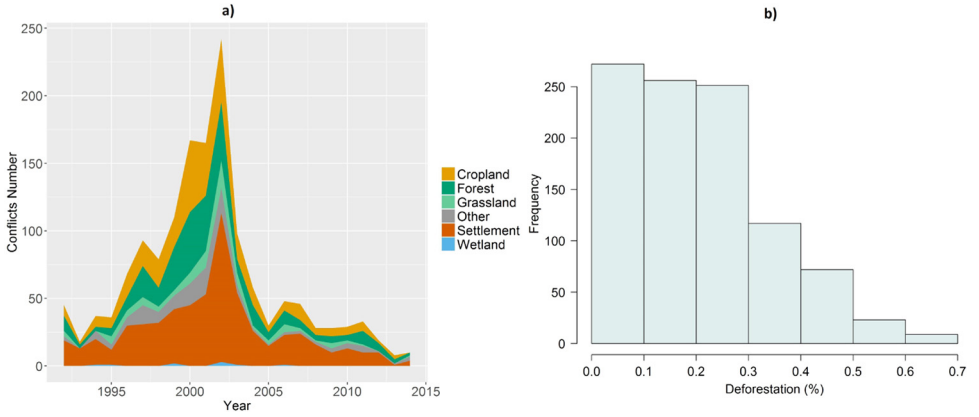

Fig. 6. Land use of georeferenced conflict locations in Colombia (a) and deforestation simulations (b). The land use (LU) of georeferenced conflict locations (a) corresponds predominantly to urban environments, followed almost equally by forest and cropland. Conflict intensity varied over the years, reaching a peak in the early 2000s. Conflicts number refers to the number of events with at least one fatality. The real deforestation rate of conflict locations across Colombia was 1.6%, which is 8 times larger than the mean rate given by 1000 simulations with random resampling (b).

mean that areas under permanent control of a given actor are not strongly affected during armed conflict periods.

3.2. Forest land use dynamics at conflict event locations in Colombia

Conflict events in Colombia with at least one fatality took place predominantly in urban environments, followed almost equally by forest and cropland LU (Fig. 6a). Conflict intensity varied over the years, strongly increasing from 1992 and reaching a maximum peak in the early 2000s, and then sharply decreasing.

By examining the LU before and after the conflict event took place at a country scale we find that conflict locations are more likely to undergo deforestation than areas devoid of conflict ($p < 0.001$, $N = 1000$). Specifically, we find that the deforestation rate of conflict locations (1.6%) is 2.5 times higher than the maximum deforestation rate presented by the simulations (0.62%). Selecting as a benchmark the highest deforestation rate given by the simulations represents the most conservative comparison possible (Fig. 6b). In a less conservative comparison, we find that the deforestation is over 8 times higher than the mean deforestation rate of the simulations (0.19%).

In contrast, the analysis of forest regrowth does not deliver significant results. Evaluating forest regrowth after 5 years and at the end of the time period, we find that 0.5% and 2.1% of conflict events occurring on non-forest LU changed to forest LU, respectively. By observing the distribution of the percentages produced by the simulations (Fig. A.3b and c), it is clear that this LUC dynamic of conflict locations is not significantly different from areas chosen at random.

Overall, these country-scale results are consistent and serve as a validation of the first analysis of Section 3.1. Evaluated for a long-term period (1992–2015), both analyses consistently point towards an overall negative impact of armed conflict on forest ecosystems in Colombia. 'Forest regrowth pathways' occur predominantly in smaller areas and are counterbalanced by more numerous regions that present stronger deforestation dynamics.

3.3. Global deforestation dynamics at conflict event locations

Conflict events across the global tropics occurred predominantly in cropland and in urban areas, followed by forest and other LU regions (Fig. 7a). The number of conflict events across the tropics varied over the years, increasing strongly over recent years, largely as a result of an increasing conflict intensity in tropical African nations (Sundberg and Melander, 2013)

The analysis performed in the previous section is repeated for deforestation dynamics for the global tropics. By examining the LU before and after the conflict event took place we find that conflict locations are more likely to undergo deforestation than areas devoid of conflict ($p < 0.01$, $N = 100$). Specifically, the deforestation rate of conflict locations across the tropics was 2.3%, which is 2.2 and 4.0 times higher than the maximum and mean deforestation rate, respectively, presented by the simulations (Fig. 7b). Overall, these long-term global-scale results point towards an overall negative impact of armed conflict on forest ecosystems across the tropics. However, as demonstrated in the case of Colombia, diverging land use dynamics are likely to be present when considering individual countries at a sub-national scale.

4. Discussion

This study represents a long-term analysis of the diverging effects the Colombian conflict exerted on its forest dynamics across different spatial scales over two distinct periods of increasing and decreasing conflict intensity. In addition, through the examination of LUC occurring at georeferenced fighting locations, it presents the first quantified estimate of conflict events' negative impact on forest ecosystems both

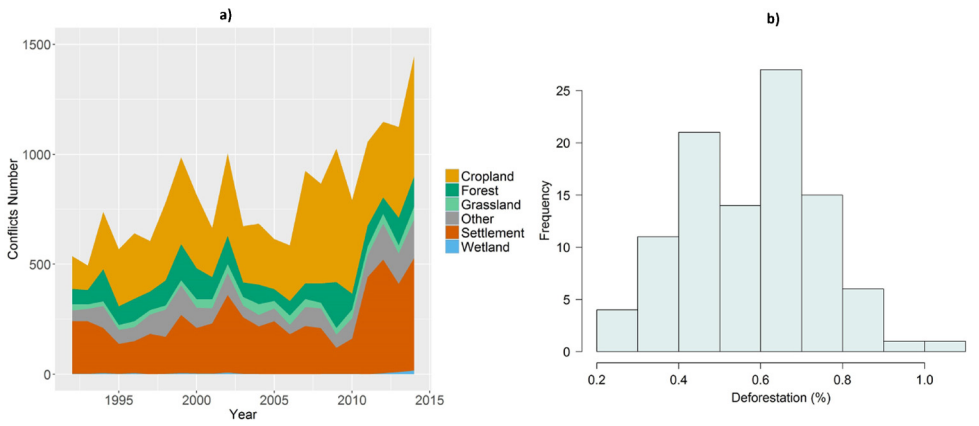

Fig. 7. Land use of georeferenced conflict locations across the tropics (a) and deforestation simulations (b). For the global tropics we observe the variation in conflict intensity over the years (i.e. number of conflict events), which shows a clear increasing trend (a). Also presented is the share of LU where these events take place. The real deforestation rate of conflict locations across the tropics was 2.3%, which is 4 times larger than the mean rate given by 100 simulations with random resampling (0.58%) (b). This indicates an overall negative impact of conflict on forests.

for Colombia and across the global tropics, which includes 66 countries (Tables A.3 and A.4).

We evaluated the environmental outcome at a municipality, department, national and global level, providing the predominant effect that armed conflict, as a consequence of altering proximate drivers of forest LUC, exerted over its forests for the 1992–2015 period. Overall, armed conflicts predominantly exerted a negative impact over forests at a country scale in Colombia and in the global tropics. The global assessment allows for the provision of a reference point: the negative impact of conflict on Colombia's forest is twice as strong as the negative impact of conflict on forests in the tropics. Assessed at a sub-national scale however, our work quantitatively highlights the long-term, diverging relationships existing between conflict and environment in Colombia, which are also likely to be present in other countries and may be investigated when finer resolution IDP data becomes available.

Building on previous knowledge (Dávalos et al., 2011; Sánchez-Cuervo and Aide, 2013; Castro-Nunez et al., 2017) this study is particularly significant for two reasons: firstly, because we assess two distinct periods of growing and decreasing conflict intensity in Colombia (1992–2015) (Fig. 6a), which lends a high degree of confidence to the pathways found in our municipalities; and secondly, it quantifies for the first time how likely a conflict-induced LUC occurs in relation to average LUCs, both in the case of the Colombian conflict and across the global tropics.

Sánchez-Cuervo and Aide (2013) assessed the effect of different socio-economic variables on woody cover change for the 2001–2010 timestep, and found that demographic variables induced by armed conflict were important at the biome and ecoregion scales, which in some areas resulted in forest regrowth. Our study highlights that the trends observed at coarser resolutions (biome and ecoregion) may vary at finer scales (municipality). For example, Sánchez-Cuervo and Aide (2013) reported that high levels of forced displacement from rural to urban areas were accompanied by a recovery of the forest cover in the Magdalena-Urabá and Chocó-Darién Moist Forest ecoregions (Fig. A.4 (Sánchez-Cuervo et al., 2012)), i.e. the 'forest regrowth pathway'. Although we appreciate the same dynamics from our study in the Magdalena-Urabá Moist Forest ecoregion, we find only partial agreement for the Chocó-Darién ecoregion. At a finer scale we can observe that some municipalities like Tumaco, known for high levels of coca crop cultivation, also present the opposite 'deforestation pathway' within this ecoregion (Fig. 5a).

Similarly, deforestation-induced conflict was reported to occur in the Northern Andean Montane ecoregion, driven in some cases by gold production. These results are partly supported through our analysis: we find several municipalities displaying the 'deforestation pathway', particularly in the northern and southern parts of this ecoregion. Finally, Sánchez-Cuervo and Aide (2013) also report strong armed conflict influences in the Llanos ecoregion, an area that represented an important source of funding for illegal armed groups as well as an essential strategic corridor between the Venezuelan border and central Colombia. This is an interesting example of two opposing conflict-forest mechanisms operating simultaneously (Fig. 4). Our results suggest that the latter effect could have been more prominent, given that many municipalities of this ecoregion present a 'forest regrowth pathway' (Fig. 5a). Overall, evaluating the conflict-forests relationship at a finer scale allows to better understand the competing region-specific mechanisms underpinning LUC.

At a global scale, the different mechanisms explaining the relationship between armed conflict and forest dynamics were recently summarized in a review by Baumann and Kuemmerle (2016): on the one hand, a socially and politically unstable environment resulting during periods of conflict may increase the illegal use of natural resources such as timber and minerals, including in protected areas. Additionally, forest depletion may progress as rebel groups seek to finance themselves through different activities or as smallholder farming increases after urban-to-rural migrations induced by conflict. On the other hand, regions with unstable conditions may slow down commercial timber and mining concessions if deemed to risky. Moreover, cash crop production may diminish as access to international markets is limited or if international investments are reduced. Finally, forests may expand at the expense of cropland if farmers are recruited by rebel groups or are forced to flee. Our analysis of the Colombian conflict showed that, despite existing municipality-level diverging impacts of conflict on forests, at a country scale there was an overall negative impact of conflict on forest ecosystems. Similarly, our global results show that tropical forests suffered from armed conflict, despite multiple mechanisms operating divergingly across different countries.

In this work we derive useful insights for future studies tackling the conflict-LUC relationship. At a sub-national scale, we found IDPs to better represent varying degrees of armed conflict intensity in comparison to utilizing conflict casualties. Large numbers of casualties occurring in a single fighting event might not translate into relevant changes in local population dynamics. Furthermore, it is more likely to find data on IDPs than casualties at a municipality level for low intensity armed conflicts. IDPs also present the advantage of explicitly informing on the population dynamics directly affected by armed conflict.

Colombia's IDP dataset is particularly impressive, providing municipality-level data for the past 30 years. Improving the spatial resolution of IDP datasets in conflict ridden-countries, which at the moment rely on recent country-scale data (UNHCR, 2018), would help to advance our understanding of the spatially-divergent relationships found between conflict and forests in other countries. However, the georeferenced conflict location LUC methodology developed in this study can be built upon to assess conflict-induced LUCs occurring across different regions.

The results obtained are relevant to the sustainable development goals (SDGs) (UN, 2015), particularly to the understanding of the existing interactions across SDGs (Pradhan et al., 2017). Our work provides insights on the complex relationship existing between SDG 15 ('Life on land') and SDG 16 ('Peace, Justice and Strong Institutions'), and presents two methodological approaches to tackling this relationship in a reproducible way across countries.

Our work presents nevertheless some limitations. Firstly, the two different methodological approaches do not clarify which individual mechanism contributed the most to the changes in forest dynamics (Fig. 4). Relating the different armed conflict variables directly to underlying deforestation drivers instead of forest LU is difficult due to the unavailability of data for Colombia, particularly for periods prior to 2005. Although performing a correlation analysis does not guarantee per se the existence of a causal link in the relationship, we are confident that the causality relationship is clear for Colombia, given the abundant literature describing during the last decades the main conflict-induced factors affecting deforestation and forest regrowth (Suarez et al., 2017; Dávalos, 2001; Álvarez, 2003; Sánchez-Cuervo and Aide, 2013; Rincón-Ruiz and Kallis, 2013; Álvarez, 2001).

Secondly, even though the likely reason for municipalities presenting weak relationships between armed conflict variables and forest LU dynamics is precisely that they are non-existent, in some cases this relationship could have existed for short periods of time. Alternatively, opposite relationships could also have been possible during two separate periods, since areas controlled by different armed conflict actors change over time (Echandia, 1998). Although unlikely to hold for many, for these Colombian municipalities we cannot say that armed conflict did not impact their forest ecosystem at a given point in time, only that in the long term its effect was not observed.

Thirdly, Colombia's > 50-year conflict is extremely complex and numerous simplifications are necessarily required when attempting to address our research questions, for instance in relation to the armed conflict variables chosen that can describe with sufficient reliability different degrees of conflict intensity. Although different actors involved in the conflict likely impacted natural resources and local

population dynamics differently (Álvarez, 2003), we did not attempt to disaggregate armed conflict impacts by different participating actors.

We advise against extrapolating conflict-period conclusions, or the use of conflict-period variables, to post-conflict scenarios: variables that adequately described the relationship pathway between armed conflict and forest LU during conflict periods do not necessarily hold for post-conflict periods, where rapid socio-economic and political transitions create a whole new set of operating frameworks (Sierra et al., 2017). To illustrate, an increase in Colombia's deforestation rates has been observed [see e.g. Terra-i (Reymondin et al., 2012)] since the recent peace agreement despite the evident decrease in the number of IDPs. This highlights the potential risk of using the same lens for evaluating conflict and post-conflict periods and calls for special care.

There are substantial research opportunities in the burgeoning research field of armed conflict and LUC (Baumann and Kuemmerle, 2016). In regards to Colombia, its post-conflict period holds many open questions, for instance in regards to the rate and nature of change in deforestation drivers, the return of displaced population, policy trade-offs between peace building and environmental conservation, or the propensity of smallholders to conserve forests in areas that were especially afflicted by the armed conflict (Suarez et al., 2017; Castro-Nunez et al., 2016). At a global scale, LU GHG emissions should decrease non-linearly and reach 0 by 2050 in order to meet the 1.5° climate target (Rockström et al., 2017). However, global LU GHG emissions remain very high, despite having experienced a slight decrease in recent years (Ganzenmüller et al., 2019). Although the number of conflicts worldwide is increasing (Sundberg and Melander, 2013), the relationship between armed conflict and LUC still remains largely unexplored at a global scale, and therefore its impact on GHG emissions continues to be unknown.

5. Conclusion

This study represents a municipality level, long-term spatial analysis of the diverging effects the Colombian conflict exerted over its forest dynamics over two distinct periods of increasing and decreasing conflict intensity. Additionally, it provides the first global assessment of the relationship between conflict and deforestation across the global tropics. We identified IDPs as the most suitable variable to represent varying degrees of conflict intensity at a sub-national scale and, through the examination of Colombian municipalities during the 1992–2015 period, distinguished both negative and positive effects of armed conflict on forests for 139 and 47 municipalities, respectively. However, albeit finding positive impacts at a municipality scale, at a higher departmental level it is clear that the armed conflict exerted predominantly a harmful impact over forest ecosystems. This negative impact is further confirmed through a first LUC analysis of georeferenced conflict locations in Colombia, where we find that conflict areas were 8 times more likely to undergo deforestation in relation to average deforestation rates. The need to finance conflict efforts in Colombia increased proximate deforestation drivers such as illicit crop production, mining and logging. In addition, insecure land tenure and unstable political institutions increased the phenomenon of smallholder land grabbing and ensuing cattle pasture expansion, which is driven by the perception of future land value and unrelated to cattle ranching revenues. At a global scale, conflict areas were 4 times more likely to undergo deforestation in relation to average deforestation rates, despite diverging mechanisms likely operating across different regions. The relationship between armed conflict and LUC is of global relevance given the recent increase of armed conflicts across the globe and the importance of a possible exacerbation of armed conflicts and migration as climate change impacts increase. It is important to improve our understanding of the effect that conflict and migration exert on LU and on forests in particular, because of the potential feedbacks in terms of GHG emissions and reduction of key ecosystem services.

Conflict of interest

None.

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Appendix A. Supplementary Data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.gloenvcha.2019.03.006.

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